SEISMIC MODELLING OF MINNELUSA REFLECTIONS, POWDER RIVER BASIN, WYOMING

Introduction

The seismic method of geophysical exploration predominates over other geophysical methods due to its high accuracy, high resolution, and great penetration. The controlled energy sources used in seismic exploration generate seismic waves which travel outward from the location of the explosion. The basic technique used in seismic exploration consists of the generation of seismic waves and the measurement of the time required for the waves to travel from the energy sources to a series of geophones which detect the resulting motion of the earth. Reflections of seismic waves are generated by discontinuities such as an abrupt change in elastic properties, impedence contrasts and density contrasts. The geophones will detect both direct and reflected waves along with some undesirable noise.

The reliability of seismic methods is very strongly dependent upon the actual quality of the records. The energy received at the surface does not just consist of direct and reflected waves. Seismic noise is usually a problem with the records in that signals irrelevant to the structure and lithology of the area are recorded. Diffractions are seismic waves emitted from point sources that produce symmetric anticlines on a seismic section. These can easily be mistaken for a subsurface structure. Also, data washouts may occur because of the lack of penetration of energy or a scattering layer in the subsurface. These produce areas on the seismogram which lack any strong reflectors. Furthermore, faults present in the subsurface create lateral discontinuities which can be extremely difficult to trace. Lastly, the energy recorded by the geophones is not restricted to the plane of the section, therefore creating a distortion of the record.

Background

The Minnelusa Formation is comprised of several lithologies which include sandstones, carbonates and evaporites. The Minnelusa is an oil producer in the Powder River Basin, Wyoming area. Oil will continuously migrate and disperse through the earth unless it begins to accumulate due to a stratigraphic or lithologic trap. A trap can be described as a porous and permeable formation overlain by an impermeable formation. If oil is present, it will accumulate in the highest portion of the permeable formation. The mechanism responsible for trapping most of the oil presently being exploited in the Minnelusa is a combination lithologic and structural trap consisting of an erosional surface associated with a thickening of the overlying impermeable Opeche Shale. However, from preliminary seismic records and past research of the Minnelusa, a second type of trap due to a change in lithology is thought to exist. This type of trap is made possible by the regional attitude of the Minnelusa and a change of facies. The Minnelusa indicates a prominant northwest trending structural high. Furthermore, a permeable sandstone of the Minnelusa changes into an impermeable limestone at a stratigraphically higher location, thus creating a possible trap.

Procedures

The seismic record of the area of the Minnelusa in question is not dependable as a source of information due to the quality of the records being examined. Therefore, a synthetic seismogram must be constructed. A synthetic seismogram is a one dimensional seismogram which is used to calculate the amplitude and arrival times of direct and multiple seismic waves. It is made with the use of a computer program which utilizes integrated arrival times from sonic well logs. Logs from previous wells drilled into the Minnelusa will be used to construct the synthetic seismogram which will be tested for validity by comparing it to a known seismogram of an area with similar lithologies and changing facies.

Expected Results

The synthetic seismogram should help to define the stratigraphic changes that occurred during the deposition of the Minnelusa Formation along with its attitude with respect to surrounding formations. If a change in facies is interpreted and substantiated, the seismogram could define a lithologic trap and therefore indicate possible oil production from this area of the Minnelusa Formation.

Purpose

The purpose of this research is to investigate and define the reflection characteristics of the top of the Minnelusa Formation. This will enable the construction and interpretation of a synthetic seismogram. The seismogram can be used to determine changes of lithology, both laterally and vertically, along with depth of beds and their corresponding thicknesses. This project will give experience with well log interpretation, seismic interpretation, construction and substantiation of synthetic seismograms utilizing a computer, interpretation of stratigraphic and lithologic traps, and the prediction of potential future petroleum production.

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Construction of Synthetic Seismograms

by

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Submitted in Partial Fulfillment of the Requirements of the University Undergraduate Fellows Program

1985-86

Approved by:

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April 1986

ABSTRACT

Synthetic seismograms are seismic traces calculated from well log data. They provide a link between actual seismic records and borehole logs. Complete sonic and density logs are needed for the generation of synthetics. Velocity and density readings from the logs are used to calculate the acoustic impedence of the subsurface layers. Then, an impulse response of these layers is calculated using reflection and transmission coefficients. Finally, the synthetic is generated by convolving the impulse response with a Ricker Wavelet. Synthetic seismograms are very useful in determining the wave characteristics associated with changes in stratigraphy. They can be used to define such things as unconformities, and even large scale facies changes. Synthetic seismograms can only be calculated as approximations. However, they are still valuable tools for enhancing seismic interpretation.

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Construction of Synthetic Seismograms

A synthetic seismogram is a seismic trace calculated from well log data. Calculations are possible because reflectivity is related to the velocity and density of rocks and these quantities are measured by sonic and density logs. Synthetic seismograms provide a link between actual seismic records and borehole logs. Their primary use is to define wave characteristics associated with a particular interface or sequence of interfaces. Input data can be manipulated to illustrate the effects that changes in the geologic section have on the seismic record. A comparison of seismic wave shapes between the original synthetic and synthetics illustrating variation in thickness, facies changes, or removal of units can be valuable for knowing the types of wave characteristics to expect in these situations. This, in turn, can be combined with seismic modelling concepts to produce more realistic model seismic records, (Sheriff, 1977).

Retrieval of Data

Complete sonic and density logs are required to construct synthetic seismograms. A mathematical model of each log should be made so that an average velocity and density for corresponding depths in the well is obtained. This can be achieved by dividing the sonic log into small sections of varying thicknesses depending on the log, and taking an average reading over that thickness (Figure 1). Once this is completed, average readings over corresponding depths should be taken from the density

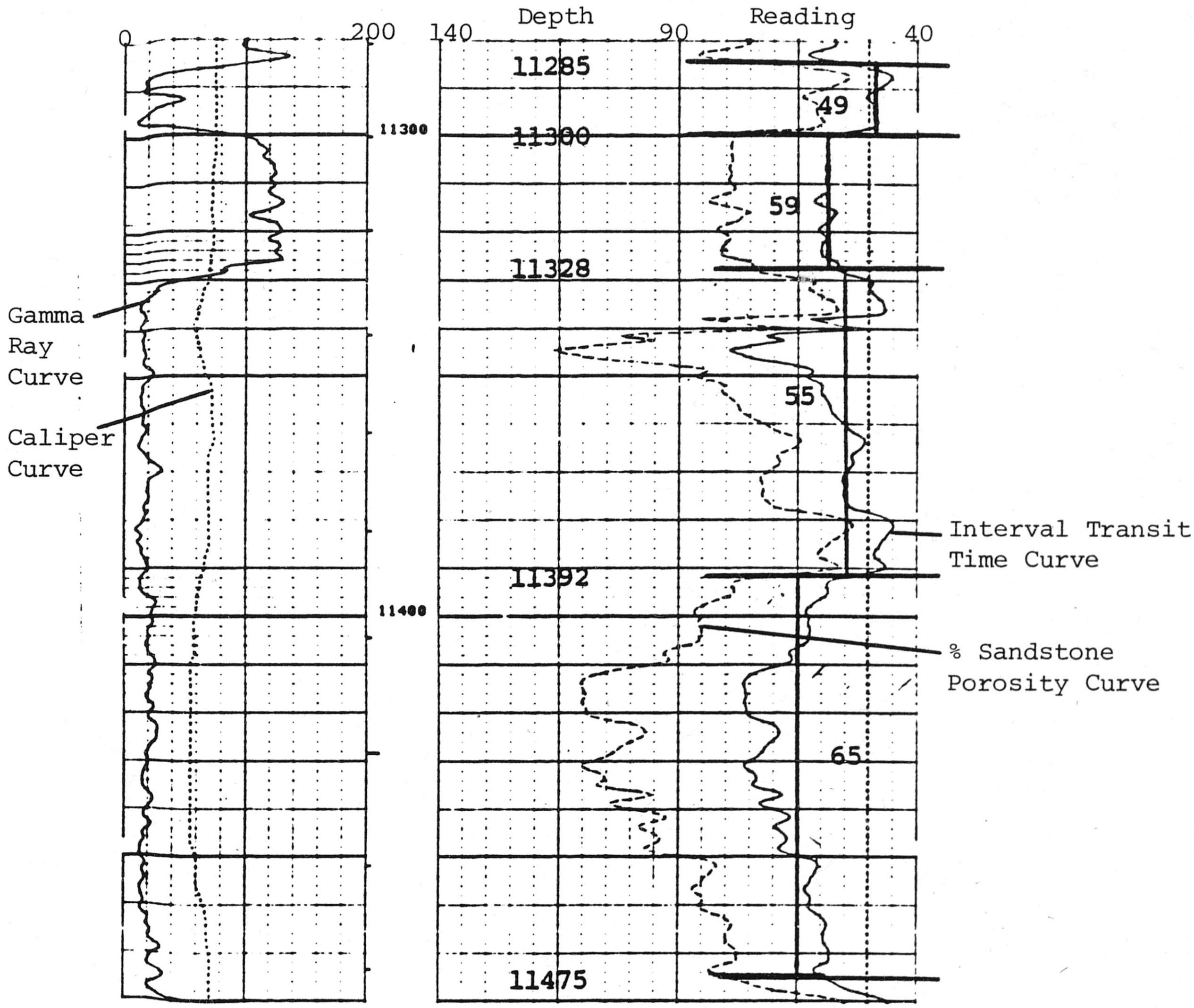


FIGURE 1 Portion of Integrated Sonic Log Indicating Average Readings and Depths.

log (Figure 2).

The sonic log is graphed as μsec/ft and the density log is recorded as percent sandstone porosity. The desired input is the acoustic impedence, which is the product of velocity and density, and the travel time through each layer. Therefore, a number of calculations must be made to structure the data into desirable form (Figure 3,4).

Model Program

Once the acoustic impedence and travel time through each layer of the subsurface have been calculated, the assistance of a computer is necessary to generate a synthetic seismogram from that model. To begin, a program designed to create files for use with an equal travel time synthetic modelling program is needed. The program deals with several layers, each of which is divided into an integral number of equal time sections called sublayers. For example, if the sublayer travel time is designated to be one millisecond, and the travel time through a given layer is three milliseconds, then that layer has three sublayers. The input to this program should be the sublayer travel time, the acoustic impedence of each layer and the number of sublayers in each layer. The output should be in the form of a data file in which the first entry is the sublayer travel time. This should be followed by a list of numbers such that the acoustic impedence for each layer is entered once for each sublayer it contains.

Impulse Program

Next, a program designed to calculate the impulse response

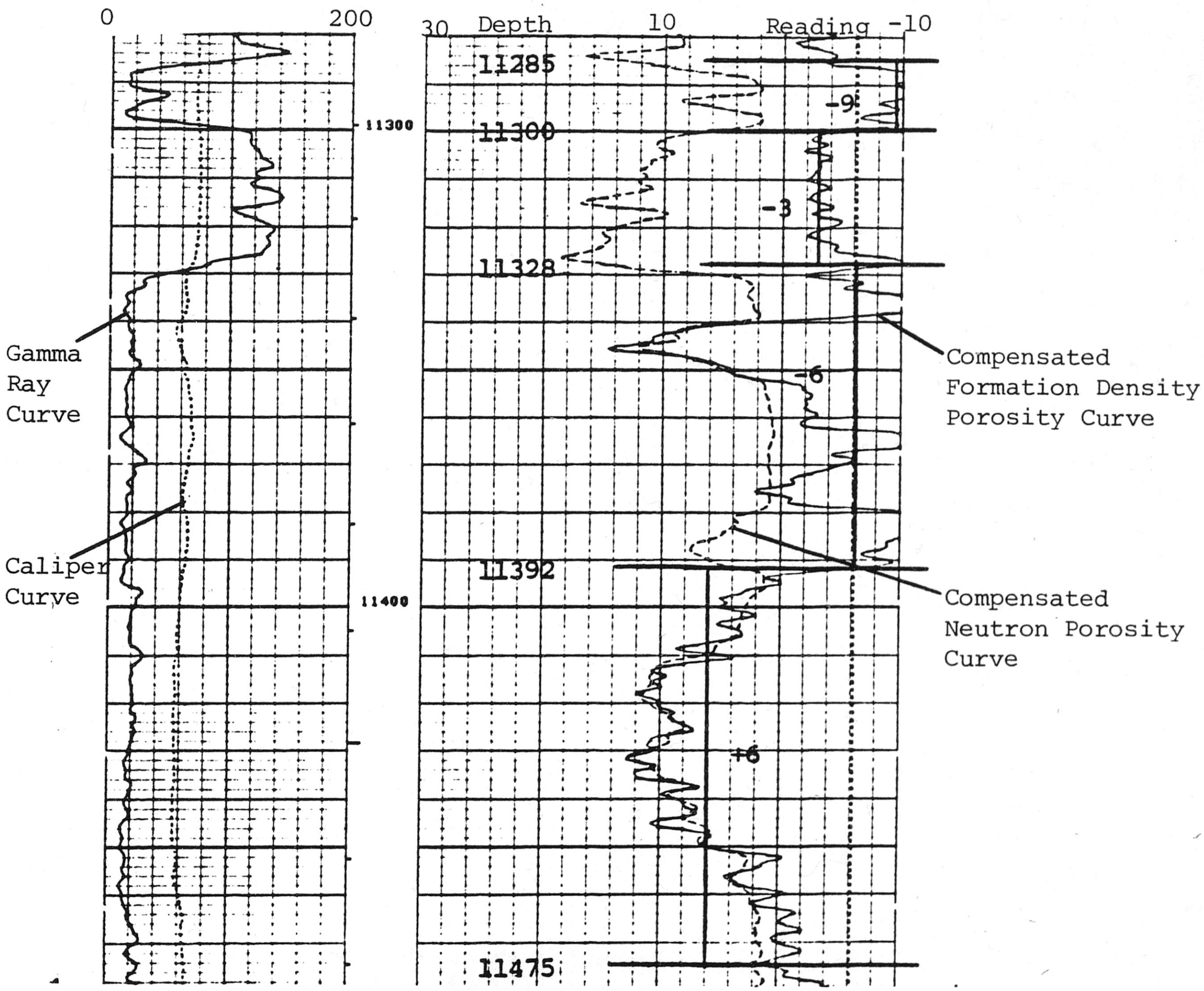


FIGURE 2 Portion of Compensated Formation Density Log Indicating Average Readings and Depths. Compensated Formation Density Porosity is expressed with a Porosity Index % Sandstone Matrix.

I. Sonic Log

A. Reading

1. Inverse Velocity: μsec/ft

B. Travel Time = 1/Velocity x Thickness

II. Density Log

A. Reading

1. Percent Sandstone Porosity

B. Bulk Density

1. $\rho_b = \phi(\rho_f) + (1-\phi)\rho_m$

where:

ρ_b = Bulk Density

ρ_f = Density of Fluid (Given on Log)

ρ_m = Density of Matrix (Given on Log)

ϕ = Sandstone Porosity (Reading from Log)

III. Acoustic Impedence

A. Z = Velocity x Bulk Density

where Z = Acoustic Impedence

FIGURE 3 Formulas for Calculations from Raw Data.

WELL Flocchini 23-1; Louisiana Land and Exploration Company; Campbell County, Wyoming

LAYER depth	SONIC LOG 1/Vel (μsec/ft)	Thickness (ft)	DENSITY LOG ϕ	ρ_B (calc)	CALCULATED INPUT Acoustic Impedance	Travel Time (msec)
11285-11300	49	15	-9	2.80	571	0.7
11300-11328	59	28	-3	2.70	458	1.7
11328-11392	55	64	-6	2.75	500	3.5
11392-11475	65	83	+6	2.55	392	5.4

FIGURE 4 Sample Data and Calculated Input for Model Program Corresponding to Log Portions in Figures 1 and 2.

of a set of horizontal layers is needed. It should be assumed that all energy is normally incident at the interfaces; there is no dispersion or attenuation within the layers; there is no loss of energy with geometrical spreading; there are infinite half spaces of air on both sides of the model; and the energy travels for an equal time in each sublayer. First, calculate the reflection and transmission coefficients of each layer. These coefficients are the solutions to the equations governing the amplitudes of the wavetrain at normal incidence to the interface. They are related to the acoustic impedence of the layers such that

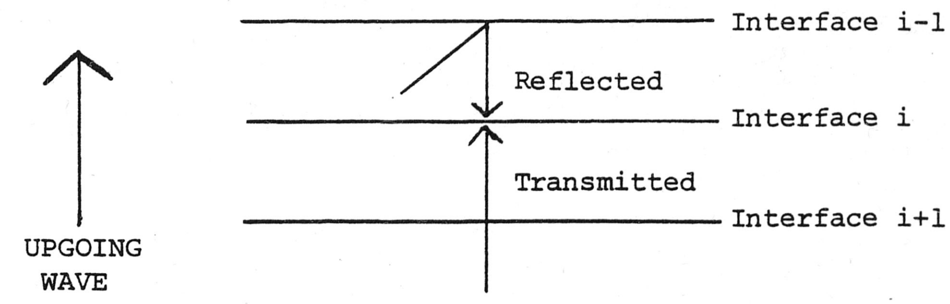
$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad , \qquad \text{and} \qquad T = 1 - R$$

where R is the reflection coefficient, T is the transmission coefficient, Z_1 is the acoustic impedence of the overlying layer, and Z_2 is the acoustic impedence of the underlying layer.

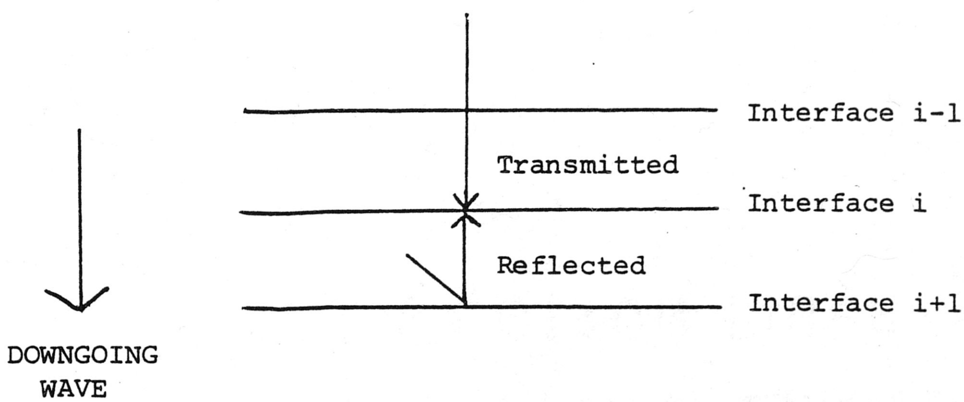
The trace is calculated by an iterative summing method. Since each layer is an equal travel time from either neighbor, there are exactly two waves exciting an interface at any increment of time (Figure 5). The input for this program should be the model data file discussed earlier, and the record length of the synthetic seismogram being constructed. The output should be another data file in which the first entries are the sublayer travel time and the record length, followed by a list of calculated amplitudes of the impulse generated by the subsurface model.

Synthetic Seismogram Program

Next, a program to generate a synthetic seismogram by convolving the impulse response of the model with an input wavelet



ampup(i) = ampup(i+1) x Tup(i) + ampdn(i-1) x Rdn(i)



ampdn(i) = ampdn(i-1) x Tdn(i) + ampup (i+1) x Rdn(i)

Where:
ampup = Amplitude of upgoing wave
ampdn = Amplitude of downgoing wave
Tup = Upgoing Transmission Coefficient
Tdn = Downgoing Transmission Coefficient
Rup = Upgoing Reflection Coefficient
Rdn = Downgoing Reflection Coefficient

FIGURE 5 Calculation of Impulse Amplitudes is needed. The input wavelet should be in the form of a Ricker wavelet (Figure 6). The synthetic is calculated by summing the impulse and the wavelet. The manner in which the two waves interfere with each other, both constructively and destructively, produces the final trace of the synthetic. This is accomplished simply by summing the amplitudes of the two waves to produce the amplitudes of the synthetic seismogram. The input to this program should be the impulse data file and a Ricker wavelet data file. The output should be a data file containing the amplitudes of the calculated synthetic. Once the synthetic seismogram has been generated, a basic plotting routine can be used to construct a graph of the results (Figure 7). Scaling factors should be carefully considered so that the synthetic can be directly compared to a seismic record.

Interpretation of Synthetics

Synthetic seismograms can be used to define the reflections characterized by means of a change in stratigraphy. This can lead to predictions of stratigraphic changes reflected in seismic records.

Synthetics can be used to locate unconformities. For example, in Figure 8, the subtle wave character differences shown at the unconformity could be defined by synthetics. Here, where the Minnelusa Formation is thicker, there is a distinctive high-amplitude waveform at the Spearfish - Minnelusa contact. However, where the Minnelusa is truncated and thinned by the unconformity, the result is multiple, lower amplitude reflections. Therefore, it could be surmised that a distinct waveform change should be associated

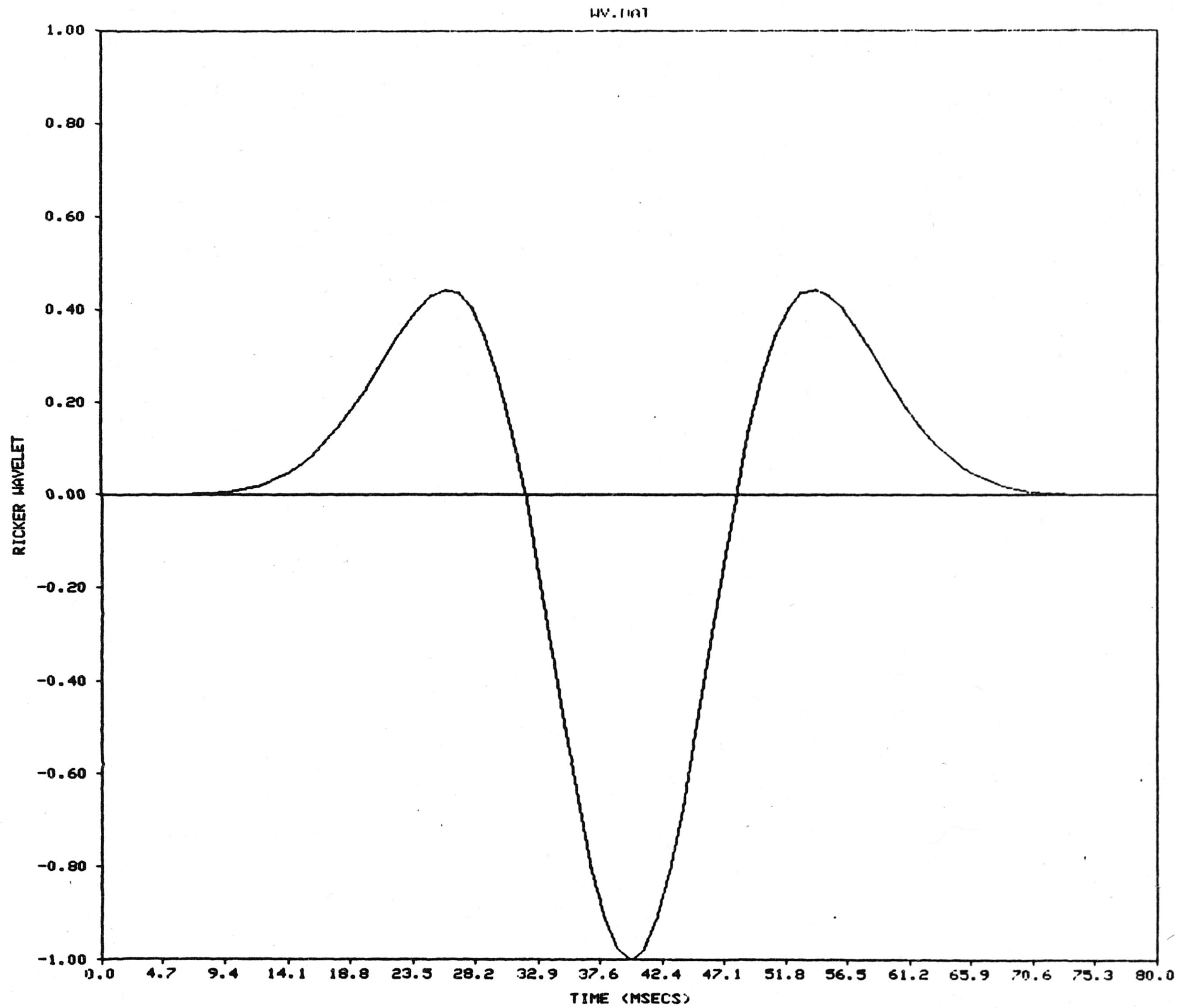


FIGURE 6 Ricker Wavelet Used to Generate Synthetic Seismograms.

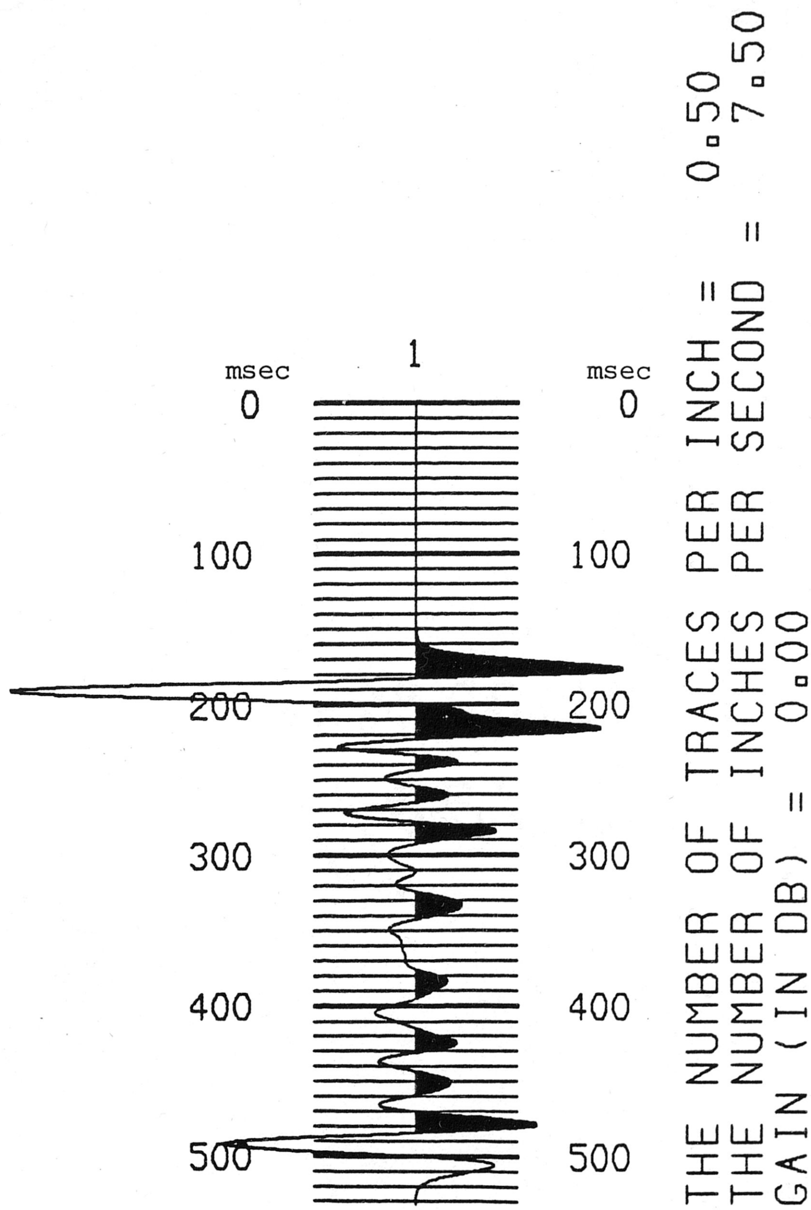


FIGURE 7 Synthetic Seismogram Generated from Well Data from Flocchini 23-1, Campbell County, Wyoming.

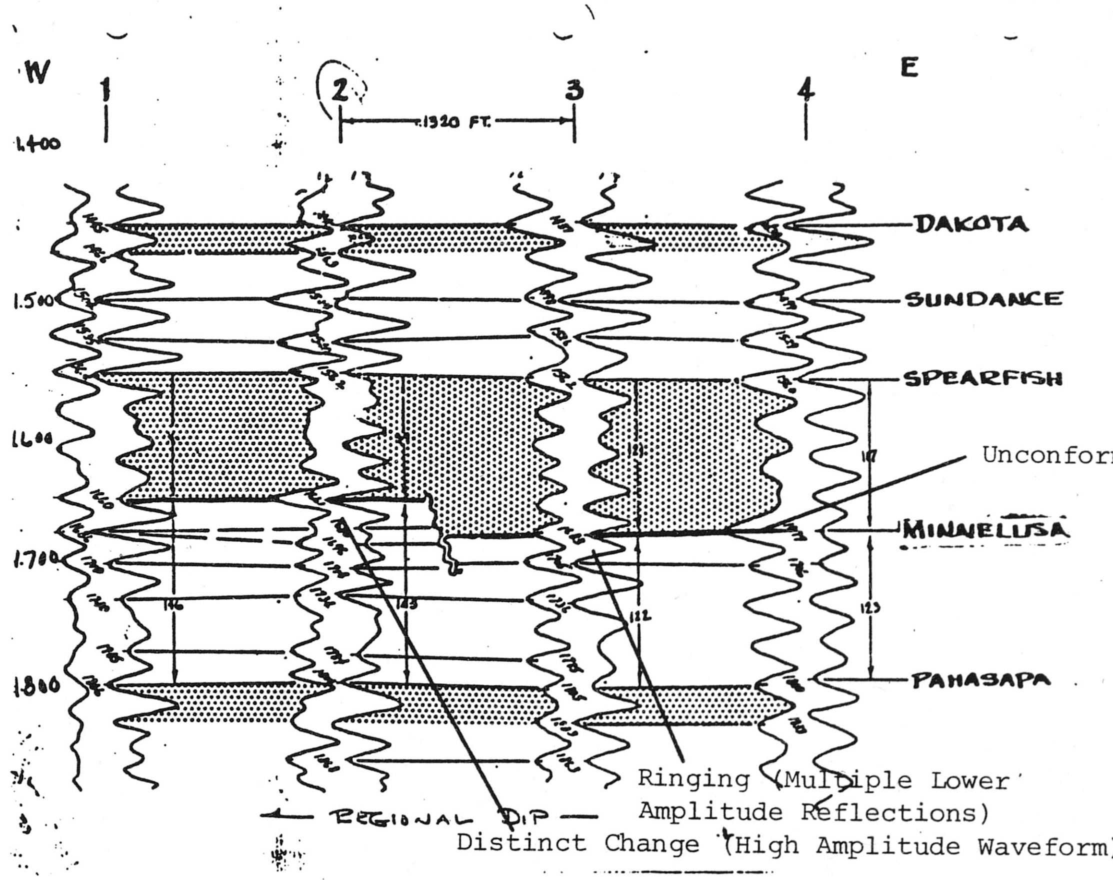
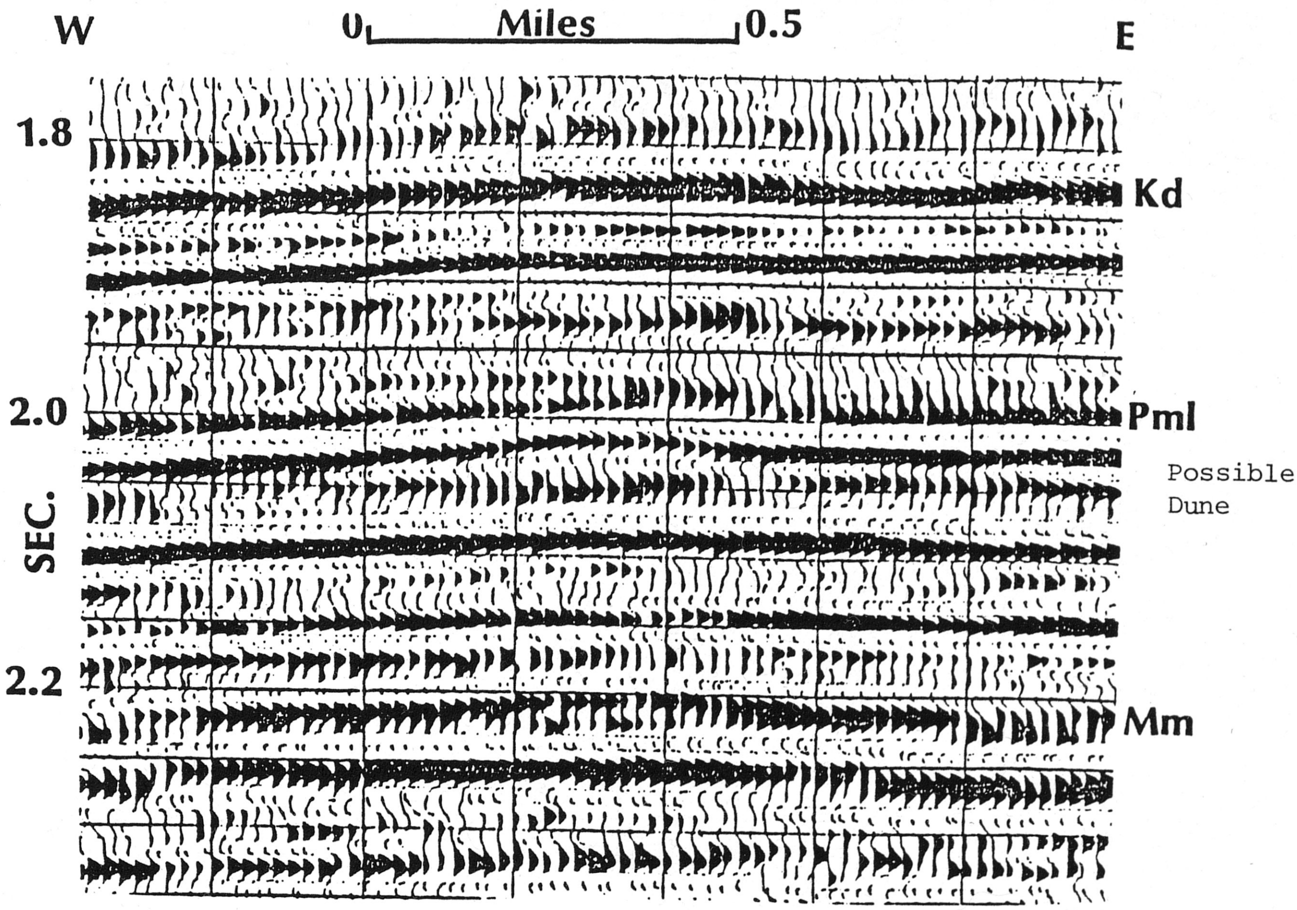


FIGURE 8 Actual Seismic Traces Indicating Changes in Waveform Associated with Changing Thickness of the Minnelusa. From R.R. Berg (personal communication).

with thick sections of the Minnelusa. When examining seismic records, the knowledge of waveform characteristics of a particular interface can make a considerable difference in the quality of seismic interpretations.

Synthetic seismograms can also be used to define and interpret large scale facies changes in complete seismic sections. Notice the large mound-like anomaly on the seismic records in Figure 9 at about 2.05 seconds. This is hypothesized to be a "possible dune buildup in the Minnelusa 'C' interval,"(Berg and Moore, 1985). This sand is believed to be a very good quality reservoir rock. Synthetics could be used to prove or disprove the C-Sand theory before drilling proceeds. This could be accomplished by manipulating the models of the subsurface until they produce waveforms similar to those of the seismic record. Therefore, with the help of synthetic seismograms, the actual facies changes associated with the anomaly on the seismic record, and the stratigraphic compositions of the layers involved could be predicted.

It should be mentioned that synthetic seismograms are not foolproof. The calculations can be done only approximately for a number of reasons. Well logs are plotted in depth while seismic traces are in two-way travel time. Logs deal with the magnitudes of velocity and density on a small scale, while seismics depend on differences in the product of velocity and density on a much larger scale. Also, a major problem in the construction of synthetic seismograms is often incomplete input data. Reliable density data is often unavailable and the upper portions of sonic



Seismic profile across a possible dune buildup in the Minnelusa "C" interval, Campbell Co., Wyo.

FIGURE 9 Seismic Profile Across Possible Dune Buildup of Minnelusa "C" Interval (Berg and Moore, 1985).

logs frequently are not measured, (Sheriff, 1977). Even with these limitations, synthetic seismograms greatly improve knowledge of wave characteristics associated with particular interfaces and variations of the stratigraphic section. Synthetics are a valuable guide to seismic interpretation.

Conclusion

Synthetic seismograms can be an aid in exploration to predict stratigraphic changes before drilling. Complete sonic and density logs are needed for their construction. A mathematical model of the subsurface is obtained from the logs. Then, an impulse response of the layers is calculated and convolved with an input wavelet to produce the synthetic. Synthetics are used to define wave characteristics associated with a particular interface or series of interfaces and changes in the stratigraphic section. Careful consideration of scale during plotting allows direct comparison of the synthetic with actual seismic traces. Therefore, location of interfaces and changes in lithology can be predicted with the use of synthetics. Studies of associated waveforms generated from synthetic seismograms can be a valuable guide for subsurface interpretations from seismic records.

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